

2016 NIAC Phase I Study
Journey to the Center of Icy Moons

Enceladus Vent Explorer Concept

PI: Hiro Ono

**Karl Mitchell, Aaron Parness, Kalind Carpenter,
Aaron Curtis, Mitch Ingham, Charles Budney, Tara
Estlin, Saverio Iacoponi, Ellie Simonson, Carolyn
Parcheta, Renaud Detry, Jeremy Nash, Jean-Pierre
de la Croix, Jessie Kawata, and Kevin Hand**

**Jet Propulsion Laboratory
California Institute of Technology**



Enceladus Vent Explorer (EVE) Goals



- Pathfinder mission concept into Enceladus vent
- Characterize the interior environment of vent
- Assess the accessibility to the subsurface ocean through vent
- Perform astrobiology and volcanology observations in the vent
- Potentially reach the liquid interface/ocean



Talk Outline

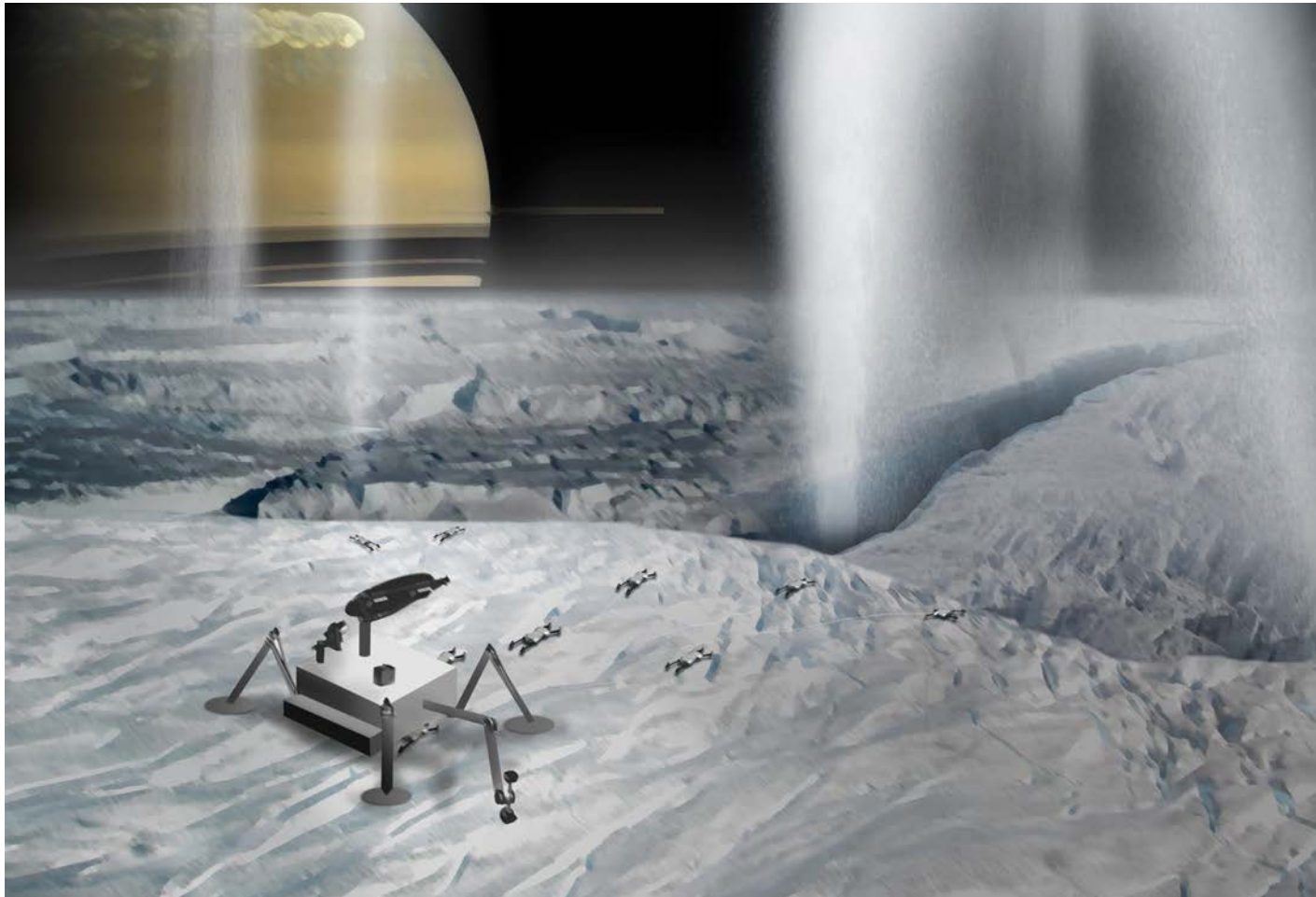


- Mission Concept
- Characterization of Enceladus Vent Environment
- Trade Studies
- Planetary Protection
- Experimental Studies
- Mechanical Prototype Design



- **Mission Concept**
- Characterization of Enceladus Vent Environment
- Trade Studies
- Planetary Protection
- Experimental Studies
- Mechanical Prototype Design

- Surface module (SM) lands near the vent (within 100s of meters)
- Tens of descent modules (DMs) are released from SM and move to the vent entrance



Force from upward flow >> gravity (0.01g)



Ice screw end effector

Linear joint

Rear section (mobility, tether spool)

Instrument section

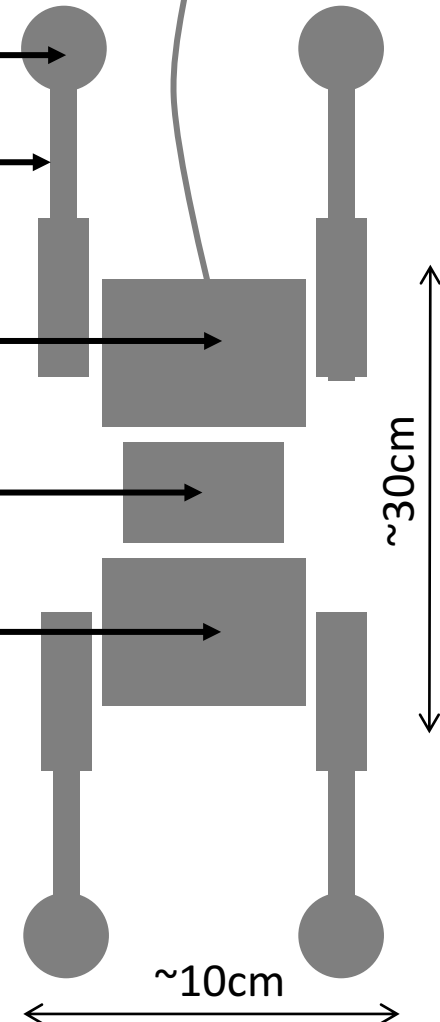
Front section (mobility, stereo camera)

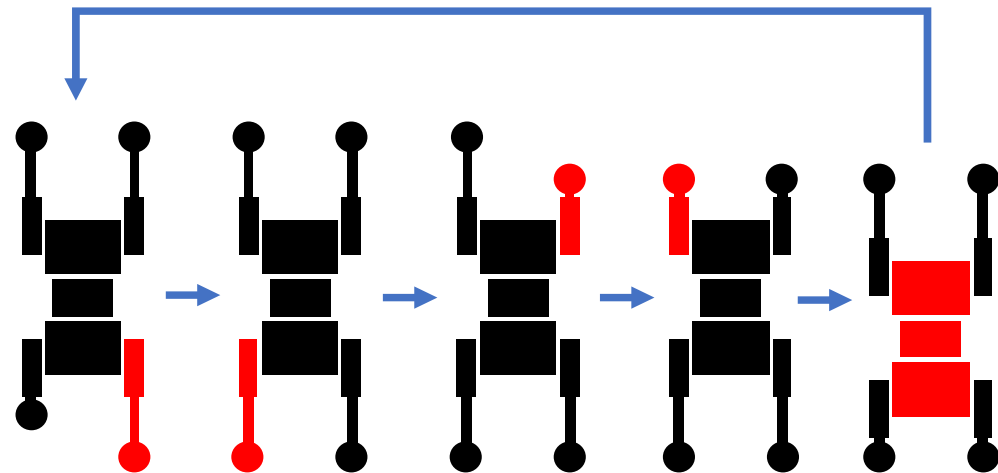
Mass: ~3 kg

Estimated speed: 5.5 m/hr

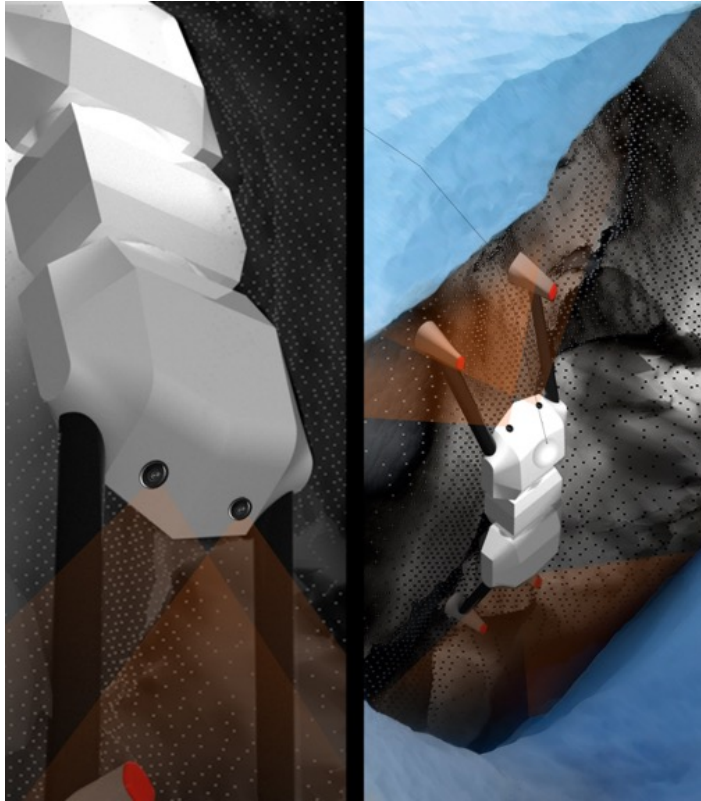
@ 10^5 Pa, 10W

SM supports power & comm via cable



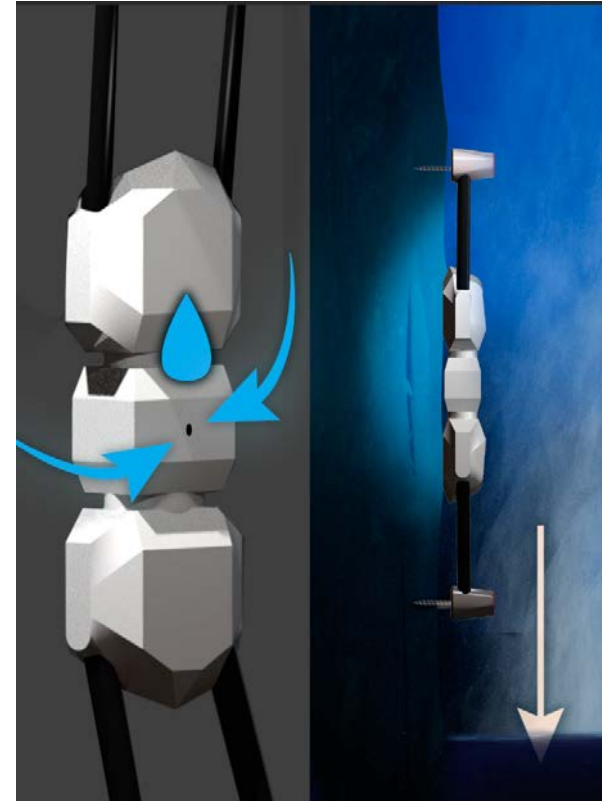


Scout DMs



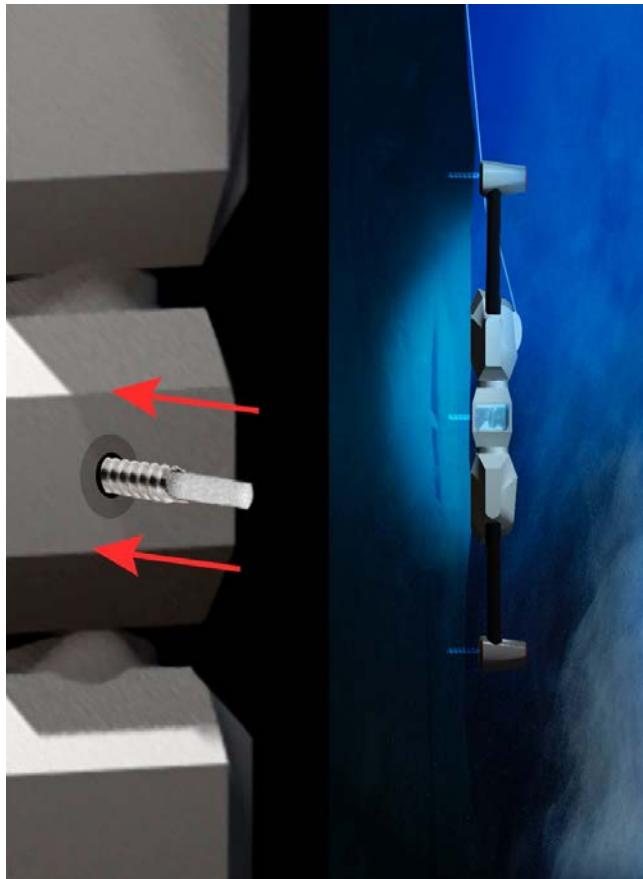
- 3D mapping of vent using structured light + stereo camera

In-situ science DMs



- Astrobiology/volcanology observations by a heterogeneous team of DMs
- One instrument per DM due to limited volume

- Collect ice cores/particles in the vent
- Return to SM for detailed analysis (e.g., mass spectrometer)
- One ice core per DM per trip for mechanical simplicity



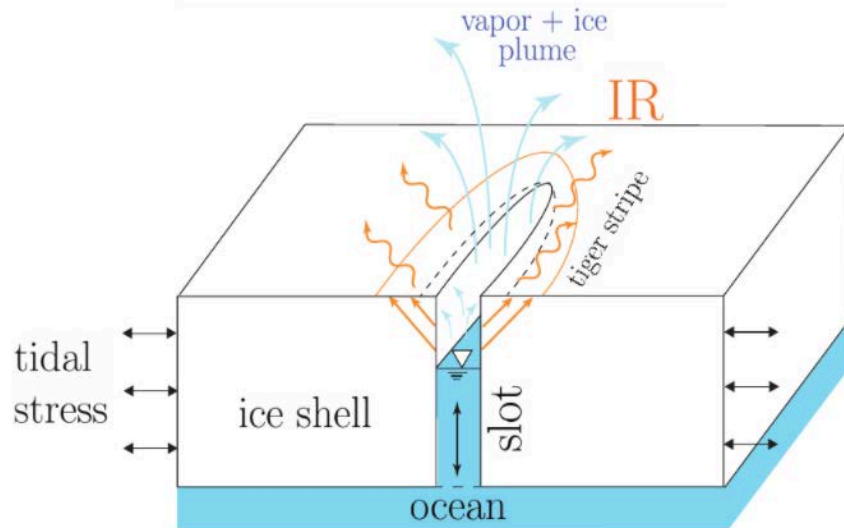


- Used Europa Lander concept's design as a reference
- Europa Lander:
 - 100 m landing accuracy
 - 45 kWh primary battery (~95kg)
 - 42.5 kg payload
 - 20-day mission
 - 5 ice samples
- EVE SM
 - Baseline power system uses RTG
 - MMRTG: 45 kg, 125W at start, 100W after 14 yrs
 - ~10 DMs + science instruments



- Mission Concept
- **Characterization of Enceladus Vent Environment**
- Trade Studies
- Planetary Protection
- Experimental Studies
- Mechanical Prototype Design

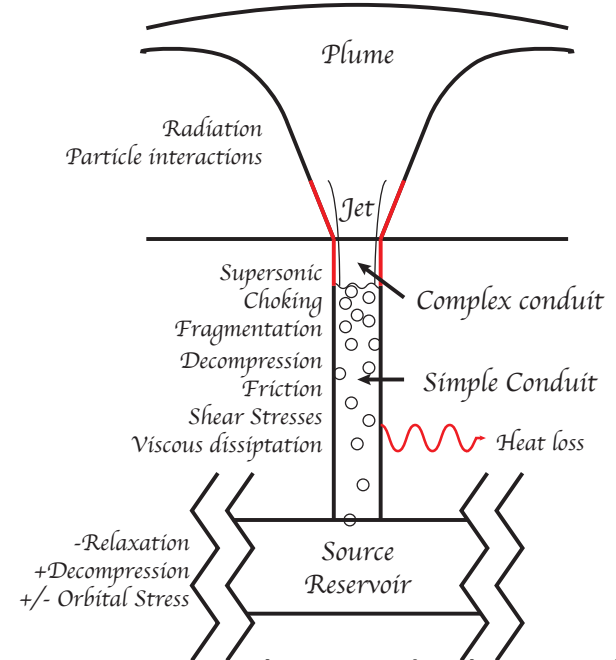
“Boiling” model



Kite & Rubin, 2016

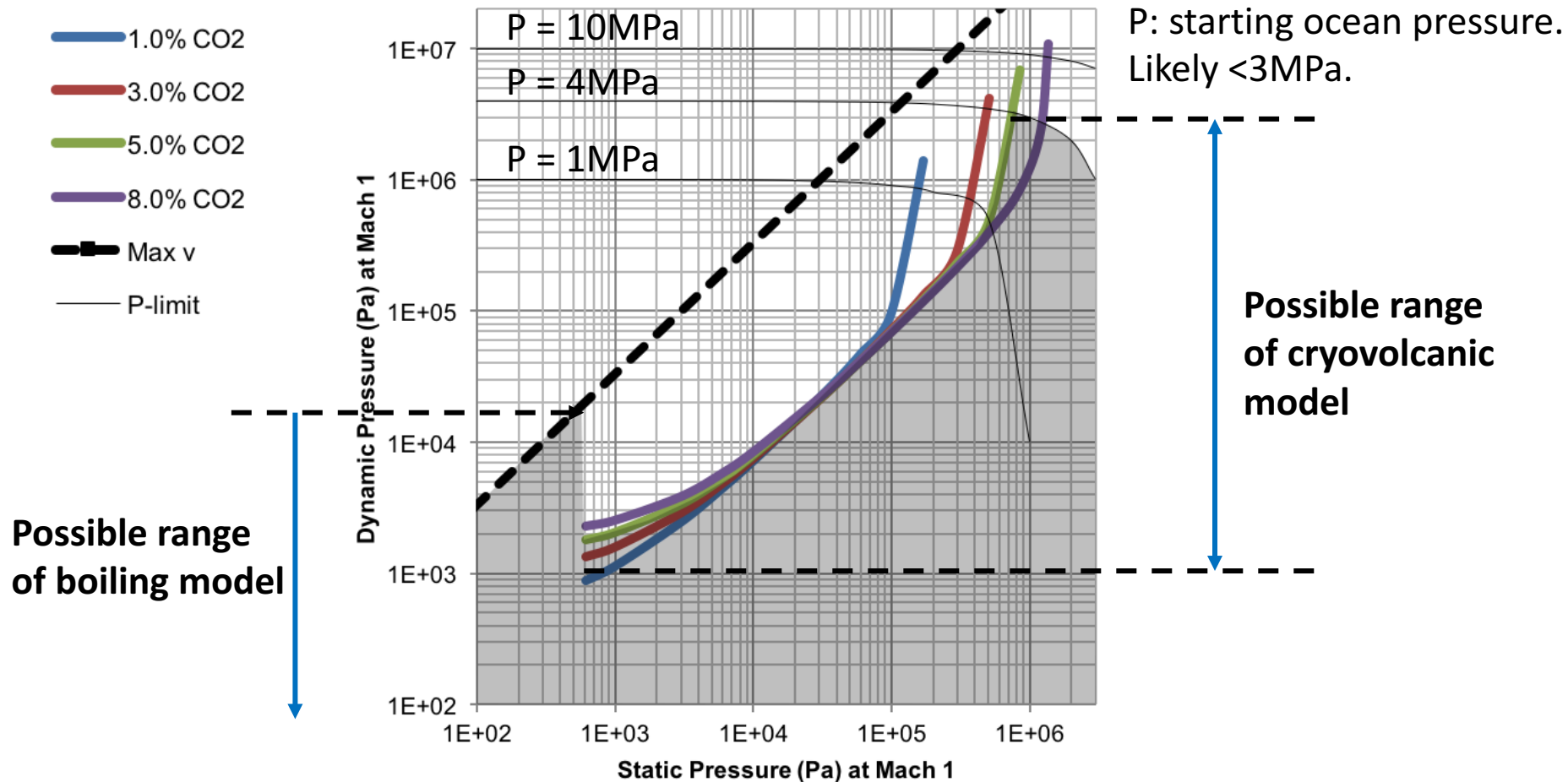
- Liquid water boils into vapor under the surface

“Cryovolcanic” model



- Ocean material ascends the conduit driven by exsolution and expansion of dissolved materials and phase changes

| | Boiling model | Cryovolcanic model |
|---------------------------------|-----------------|--------------------|
| Dynamic pressure of upward flow | $<10^4$ Pa | $10^3 - 10^7$ Pa |
| Vent width | <1 m | 1 – 30 cm |
| Feasibility of EVE | Likely feasible | Undetermined |

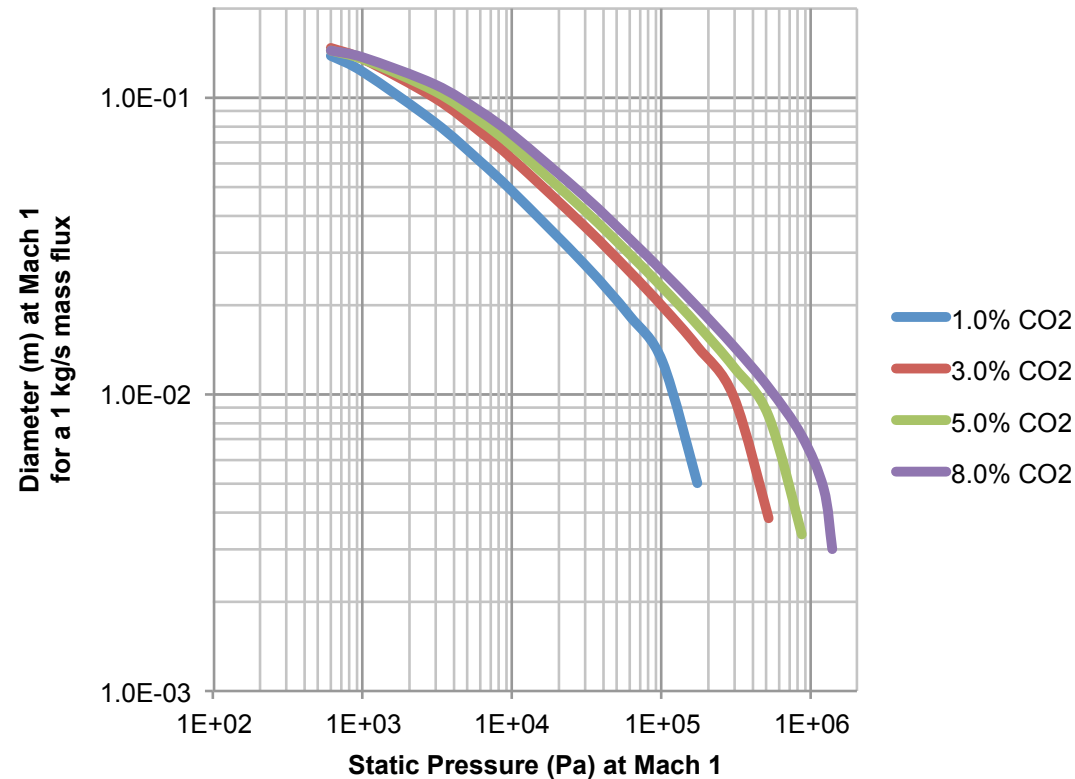


Major Assumptions

- Most of the acceleration occurs in the subsurface
- Water erupts at sub-triple points pressures
- CO₂ as a proxy for all non-water volatiles (not as the driving mechanism of eruption)
- Flow chokes (=Mach 1) at or near the surface

- Boiling model:
 - 2.5-m fissure with a very low eruption density (Kite and Rubin, 2017)
- Cryovolcanic model
 - 1-30 cm width
 - Likely evolve towards pipe-like structures
 - Driver towards the small end
 - Greater mass flux results in greater size
 - EVE would target at vent with greatest mass flux

Vent size estimate for 1 kg/s cryovolcanic vent (diameter @ choking point)

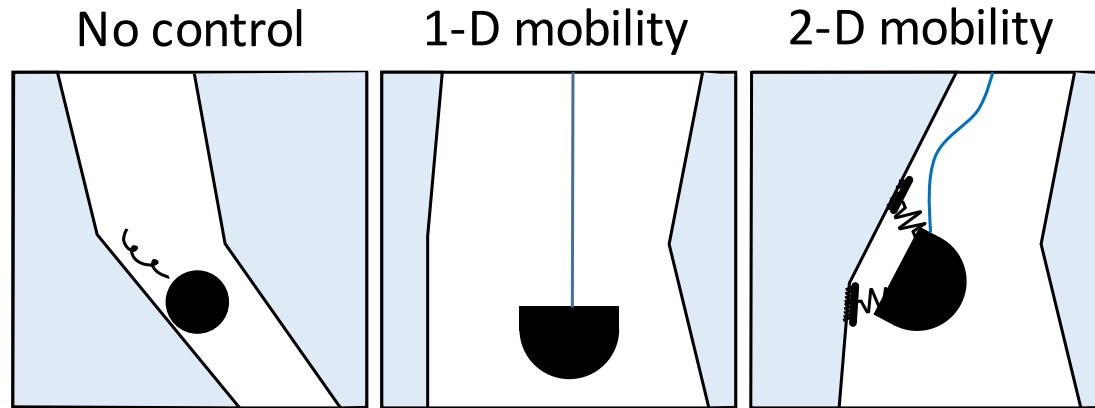




Talk Outline



- Mission Concept
- Characterization of Enceladus Vent Environment
- **Trade Studies**
- Planetary Protection
- Experimental Studies
- Mechanical Prototype Design



- Even with the most optimistic estimation of dynamic pressure (10^3 Pa), the upward force from flow is an order of magnitude stronger than gravity (0.01g)
 - Assumed a sphere with 5cm radius, 2000kg/m^3 density
 - 0.24N from gravity, 1.9N from flow
 - Needs ~ 80 cm radius for free-fall – greater than the most optimistic estimation of vent width
- **Conclusion: 2-D mobility (active descent) would be required for EVE**

Ice Screw



<http://www.pyb.co.uk/top-tips-detail.php?id=14>

Microspine gripper

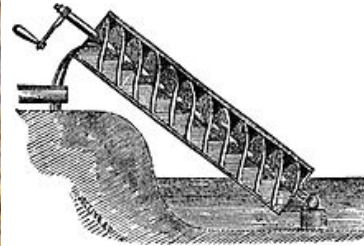


Cam/wedge

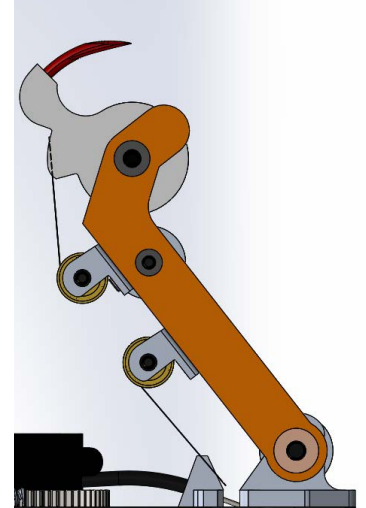


<https://diy.stackexchange.com/questions/78148/how-can-i-anchor-something-in-the-gaps-between-the-bricks-or-rocks-of-a-fireplace>

Archermedes screw



Melt anchor





Attachment Mechanism Trade Study

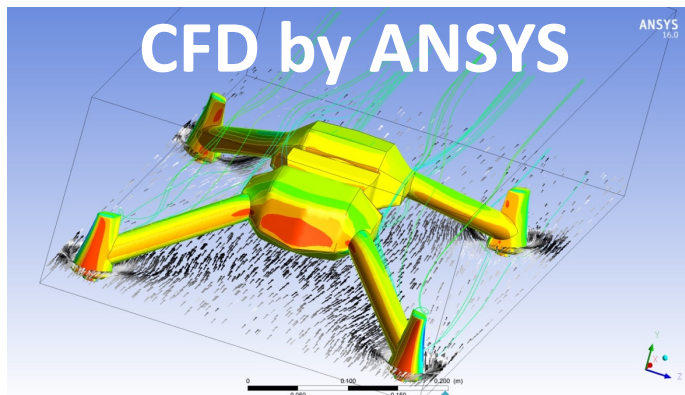
Pugh Matrix

| Design | Factor | Dynamic Pressure | Properties of the Ice | Geometry of the Conduit | Surface Roughness | Energy/Resources Required | Totals |
|---------------------------|--------|------------------|-----------------------|-------------------------|-------------------|---------------------------|------------|
| | Weight | 5 | 5 | 5 | 5 | 5 | |
| Ice Screw | | 8 | 7 | 10 | 9 | 4 | 190 |
| Microspine Gripper | | 6 | 3 | 10 | 2 | 6 | 135 |
| Cam/Wedging | | 7 | 5 | 5 | 7 | 7 | 155 |
| Archimedes Screw | | 8 | 6 | 6 | 8 | 8 | 180 |
| Melt Anchors | | 8 | 7 | 10 | 9 | 3 | 185 |
| | | | | | | | |

Rank each design in each category. 1 is the worst, 10 is the best. The weights determine the relative importance of each aspect.

| | | | | | | | |
|---|--|--|--|--|--|--|--|
| | | | | | | | |
| Hollow Interior | | | | | | | |
| Penetrates Ice | | | | | | | |
| Single Wall Capable | | | | | | | |
| >4 Actuators required for movement (Assumes limbed multi DOF) | | | | | | | |

Power System: Estimation of Required Energy



Used prototype
design in Section 6
Work by Saverio Iacoponi

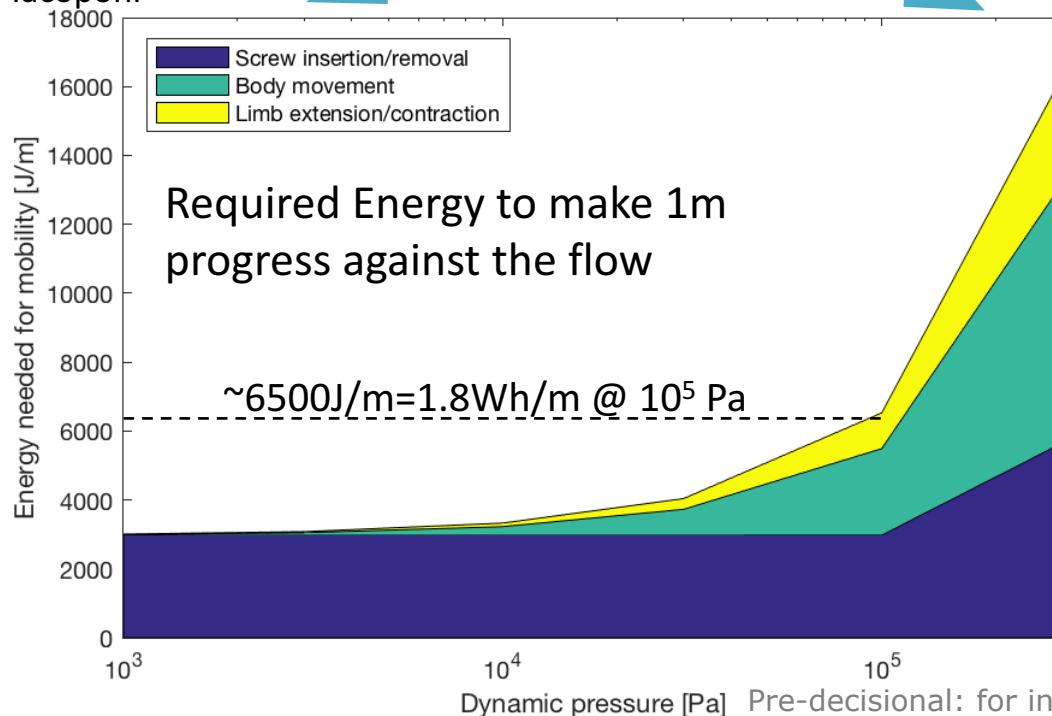
Drag force



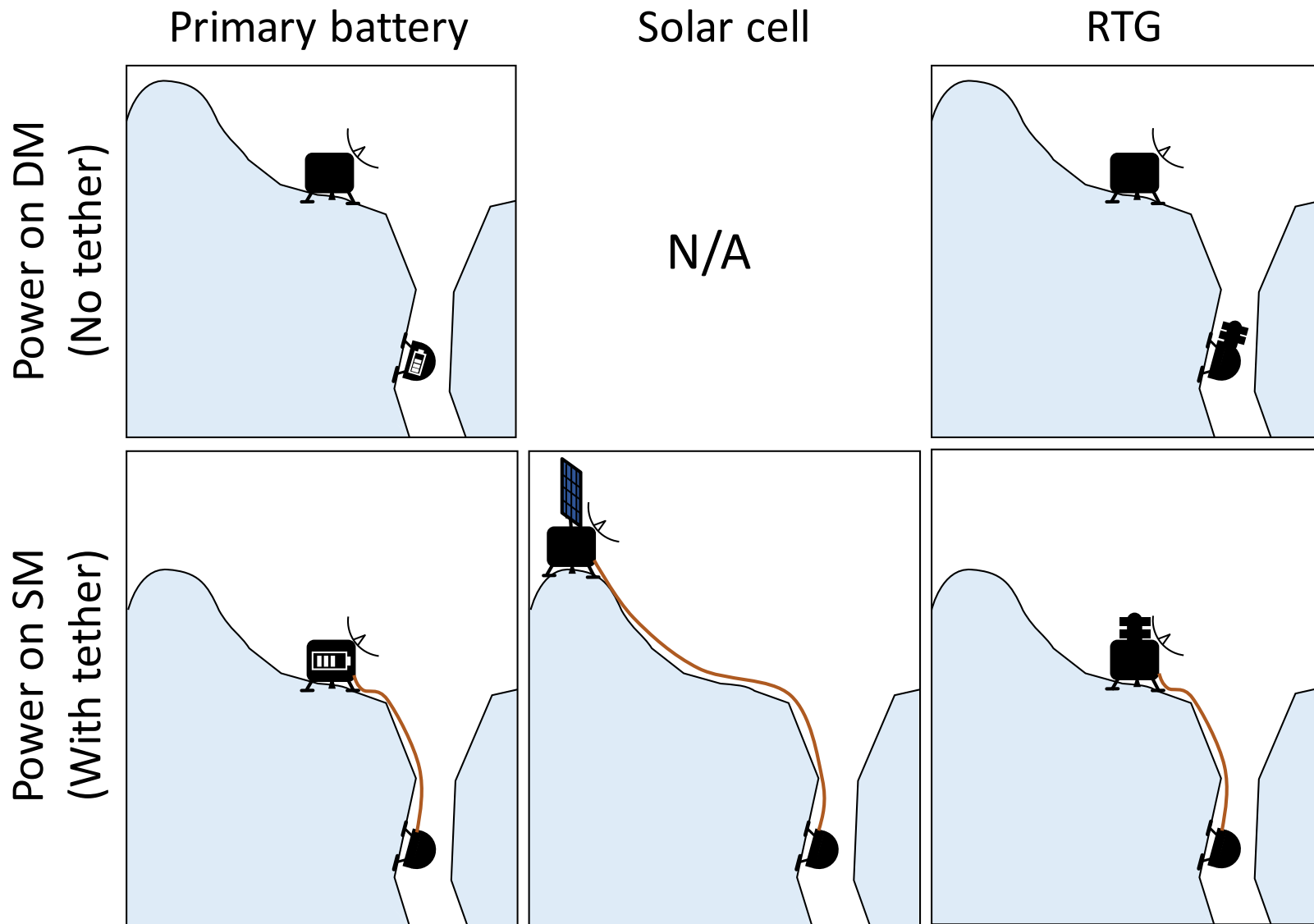
Ice chamber test

Energy for screwing in/out

Work by Ellie Simonson,
Saverio Iacoponi, Aaron
Curtis



**Estimated speed: 5.5 m/hr
@ 10^5 Pa (Assumed 10W
for mobility)**



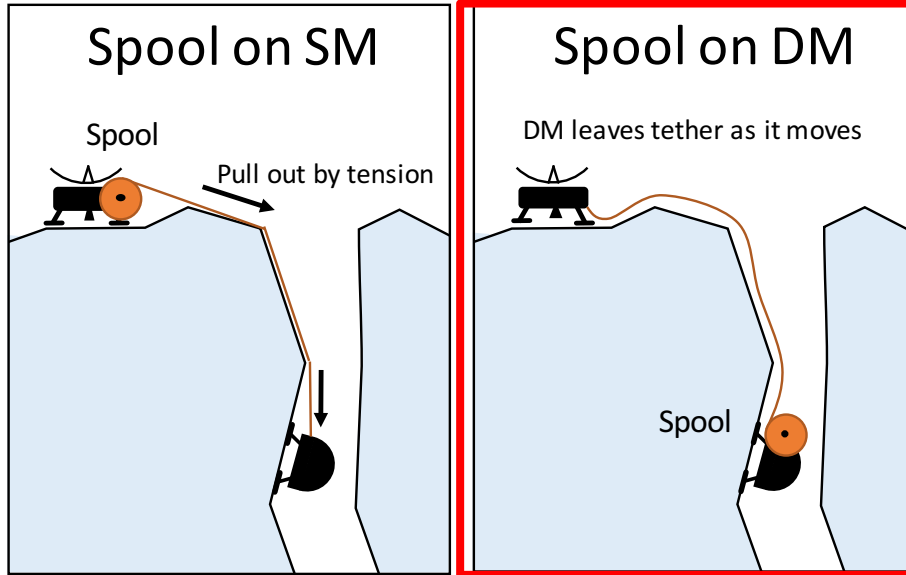
- RTG on SM would be most viable
- Power on DM would not be realistic
- Primary battery/solar cell on SM would be possible but

| Configuration | Energy source | Distance (m) | Speed (m/hr) | Max # of DMs | Major risk |
|------------------------------|-----------------|-------------------------|--------------|--------------|---|
| Power on DM (No tether) | Primary battery | 350 | 5.5 | 10 | Unreliable comm. |
| | RTG | 1300 (per year) | 0.15 | 10 | Unreliable comm. |
| Power on SM (With tether) | Primary battery | 2600 (all DMs combined) | 5.5 | 1-3 | |
| | Solar cell | | 5.5 | 1-2 | Needs at least 20 m ² solar cell; Landing site constrained by sunshine |
| | RTG | | 5.5 | >10 | |

Assumed 10W for DM mobility. The distance of “power on DM” configurations is the distance that can be traveled by each DM, while that of “primary battery on SM” is the total distance traveled by all DMs combined. The distance of “power on DM”-RTG is bounded not by available energy but by mission duration due to its slow speed. Max number of DMs of “power on DM” configurations is bounded by the payload mass of SM, while that of “power on SM” configurations is bounded by power, hence it represents the number of DMs that can be operated simultaneously. (SM can bring more DMs.)

Pre-decisional: for information and discussion purposes only

Tether system options



- Spool on SM
 - DM needs to pull out by tension
 - Need to support mechanical strength
 - Abrasion is another challenge
- Spool on DM
 - No tension needed for deployment
 - No abrasion
 - Range limited by tether length
- Tether volume/mass/resistance
 - 2km tether: 48 cm³, ~0.4kg, 600Ω
 - 10km tether: 240 cm³, ~2kg, 3kΩ
- 2 km tether is feasible for the standard three-section DM design
- 10 km tether possible with a dedicated tether section on DM

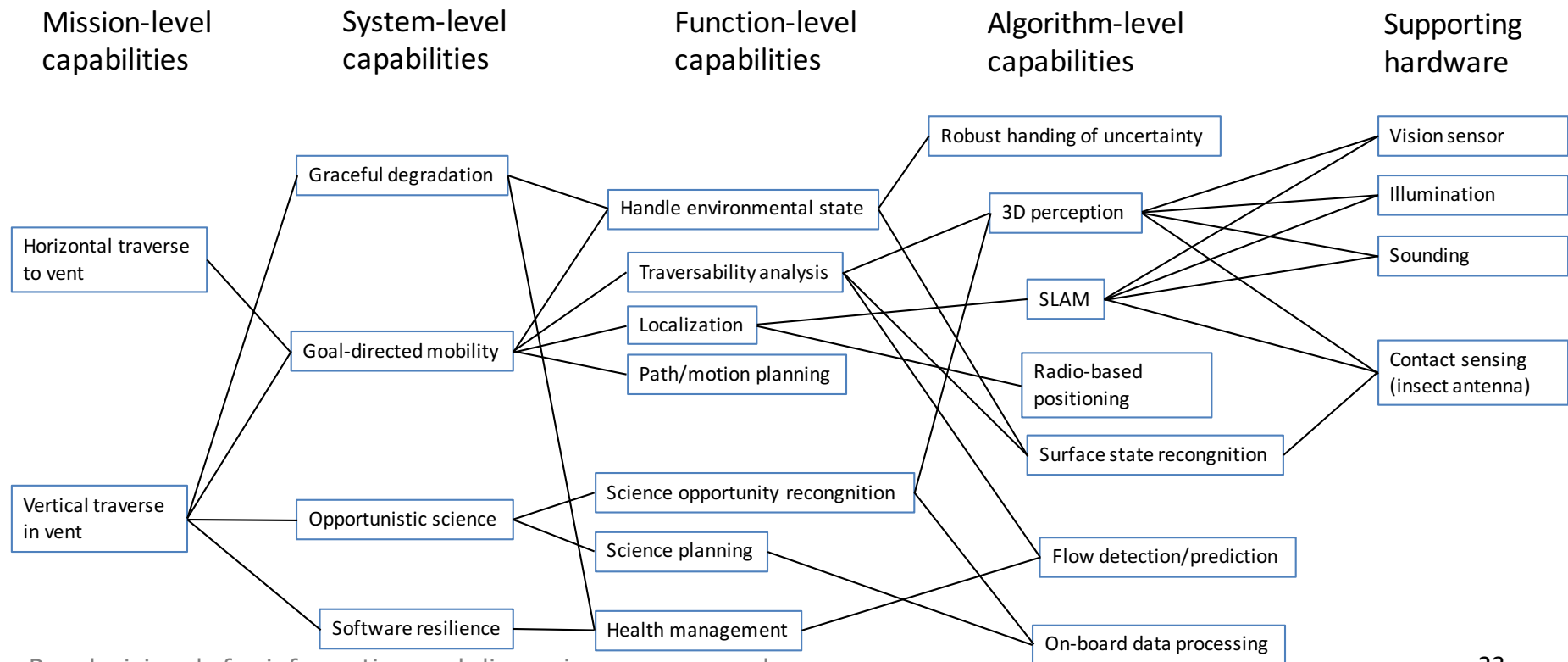


Assumption: Tether consists of three 38 AWG wires (GND, PWR, DATA)

38 AWG magnet wire
(d=0.101mm)

- High-level automation is needed for DM due to:
 - Unavailability of orbital reconnaissance - prior strategic planning impossible
 - Poor viewshed – tens of cm progress per planning cycle if manually operated
 - Multiplicity of DMs – operation tens of DM manually increases cost/labor
 - Dynamic environment - need immediate response to anomalies

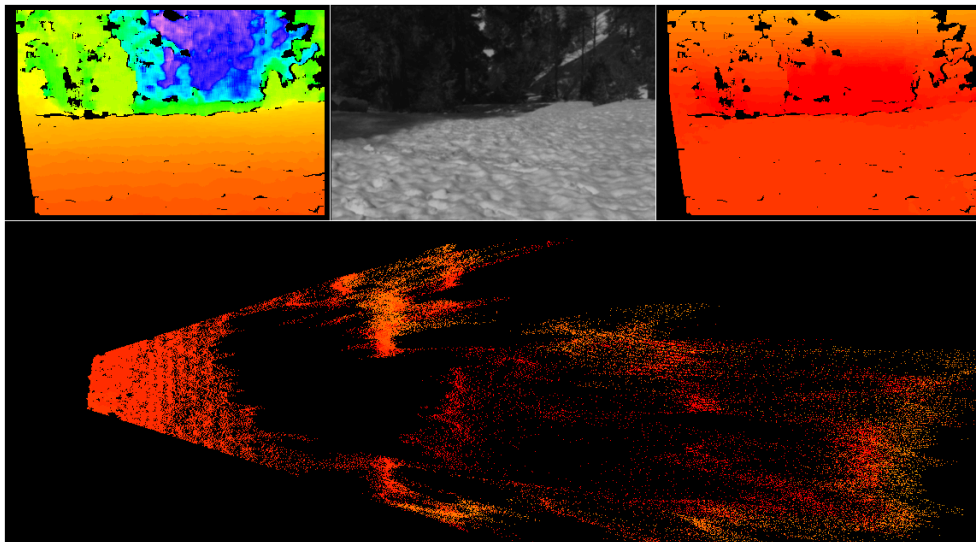
Autonomy Capability Roadmap



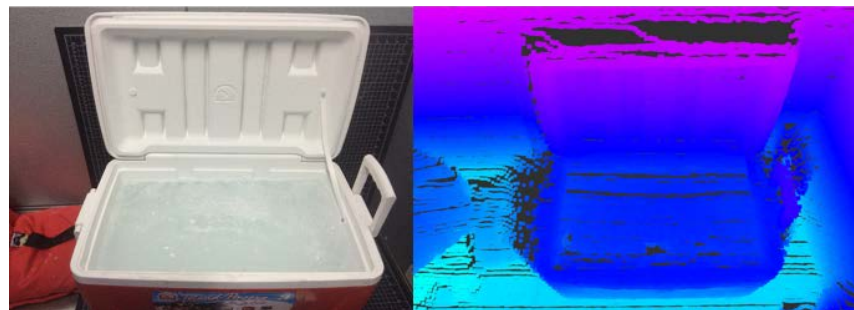
Pre-decisional: for information and discussion purposes only

Work by Mitch Ingham, Tara Estlin, JP de la Croix, Renaud Detry, and Hiro Ono

Stereo vision

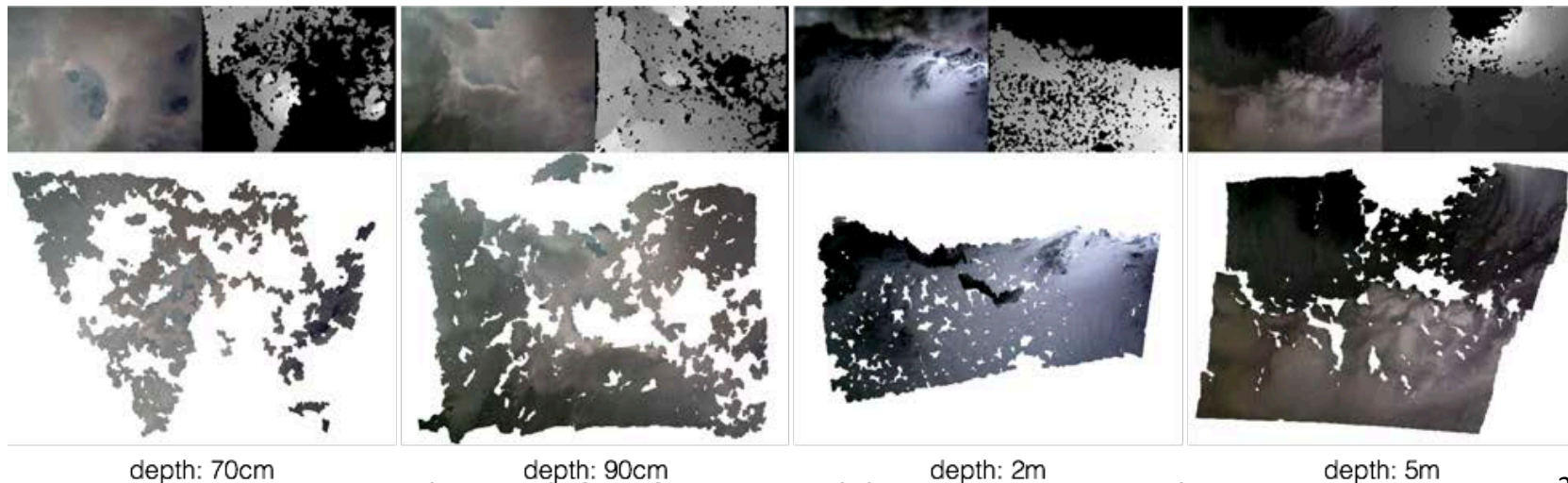


Spinning Lidar



Other options: ToF camera, Rader

Structured light



Pre-decisional: for information and discussion purposes only
Work by Renaud Detry/Jeremy Nash

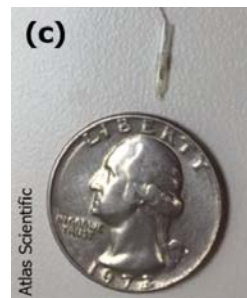


Perception System Trade



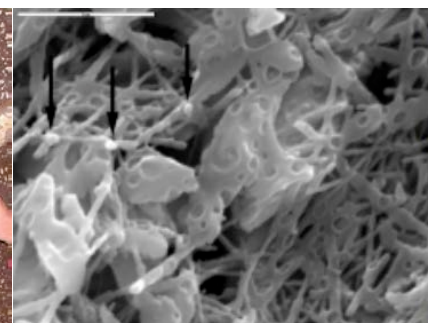
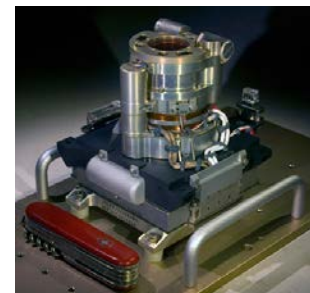
| | Power Consumption | | Device Volume | | Sensing Range | | Sensing Accuracy | | Temperature Resistance | |
|---------------------------|-------------------|---------------------------|---------------|---------------------|---------------|--|------------------|--|------------------------|-------------------------|
| Stereo Vision | 3 | 5W exposure: .1s–inf | 4 | 2x1cm ³ | 4 | 0.1m–inf (further with longer exposure) | 2 | Fails if no texture | 3 | |
| Structured Light | 3 | 7.5W exposure: .1s–inf | 4 | 2x1 cm ³ | 4 | 0.1m–inf (further with longer exposure) | 3 | | 3 | |
| Stereo + structured light | 3 | 7.5W exposure: .1s–inf | 3 | 3x1 cm ³ | 4 | 0.1m–inf (further with longer exposure) | 3 | Superior to stereo or structured light | 3 | |
| ToF Camera | 4 | >10W exposure: flash | 2 | 100 cm ³ | 2 | 0.1m–10m | 4 | | 3 | |
| Spinning Lidar | 1 | 10W scan: 5s | 1 | 100 cm ³ | 3 | 0.1m–30m | 4 | | 1 | mechanical sensitivity? |
| Radar | ≤3 | >5W | ≤2 | <4 cm ³ | 4 | ~100m | 0 | Beam width >1° range accuracy >25cm | 3 | |

- Volcanology package: temperature, pressure, flow speed
 - Vent environment & eruption mechanism
- Habitability package: pH, salinity, and oxidation-reduction potential (ORP)
 - Habitability of vent & ocean
- Microscopic imager
 - Detecting patterns indicating life
- Life detection package: microchip electrophoresis with laser-induced fluorescence
 - Detect the distribution of organics that is characteristic to life
- Each DM carries one of above

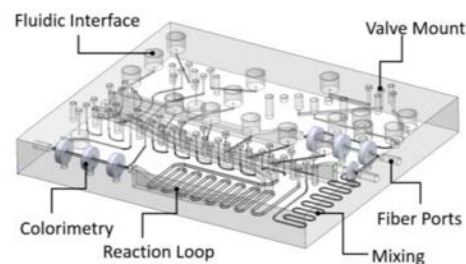


← Miniature pH probe (Kehl, et al., 2016)

MSL's Mars Hand Lens Imager (MAHLI)→



Macroscopic (left) and microscopic (right) patterns indicating life. (Jones, et al., 2008) (Boston, et al., 2001)



An example of microfluidics chip. Left: 3D printed MicroFIA manifold, right: assembled MicroFIA system. Images taken from (Kehl, et al., 2016)

Based on inputs from Peter Willis, Florian Kehl, Penny Boston, Karl Mitchell

Pre-decisional: for information and discussion purposes only



Talk Outline



- Mission Concept
- Characterization of Enceladus Vent Environment
- Trade Studies
- **Planetary Protection**
- Experimental Studies
- Mechanical Prototype Design



- Enceladus is a Category III/IV body in COSPAR/NASA PP policy (NPR 8020.12D)
- “The probability of inadvertent contamination of an ocean or other liquid water body” must be reduced to less than 1×10^{-4} per mission (NPR 8020.12D, Sec. 5.4).
- DM could directly contact the liquid body of water; significantly more elaborate bioburden reduction processing would be necessary than landing missions
- A similar level of bioburden reduction processing would be necessary for SM because
 - DMs would be in contact with SM over a long period
 - Upon a failed landing or spacecraft disintegration, SM’s RTGs (baseline power system) could melt through the ice shell and reach the subsurface ocean
- Common misconception: RTG is prohibited for icy worlds
 - There is no such rules in COSPAR/NASA’s PP policy. However, increased level of bioburden reduction would be needed to achieve the 1×10^{-4} contamination probability requirement as RTG could melt through the ice and reach a subsurface ocean over a long period.



Talk Outline

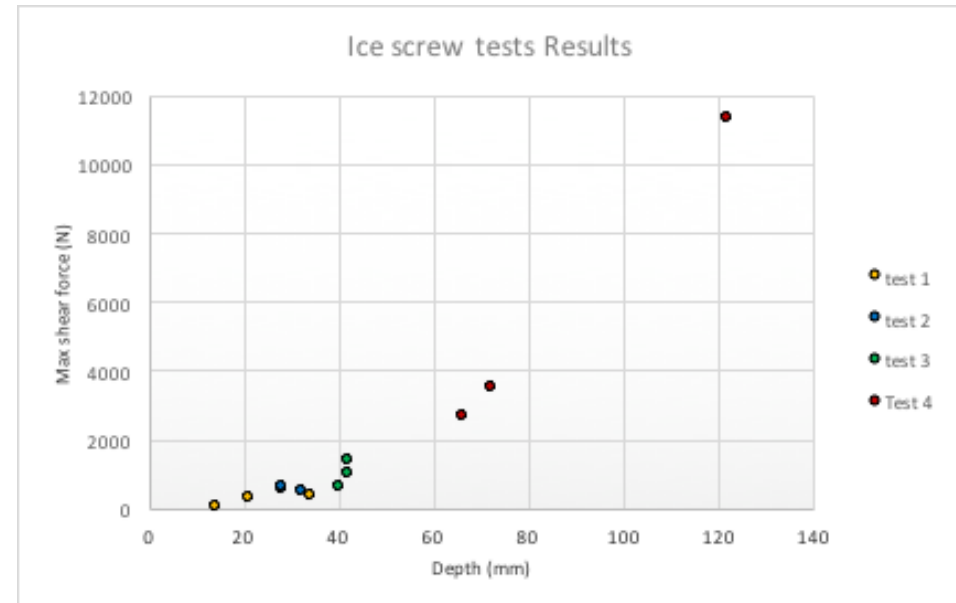
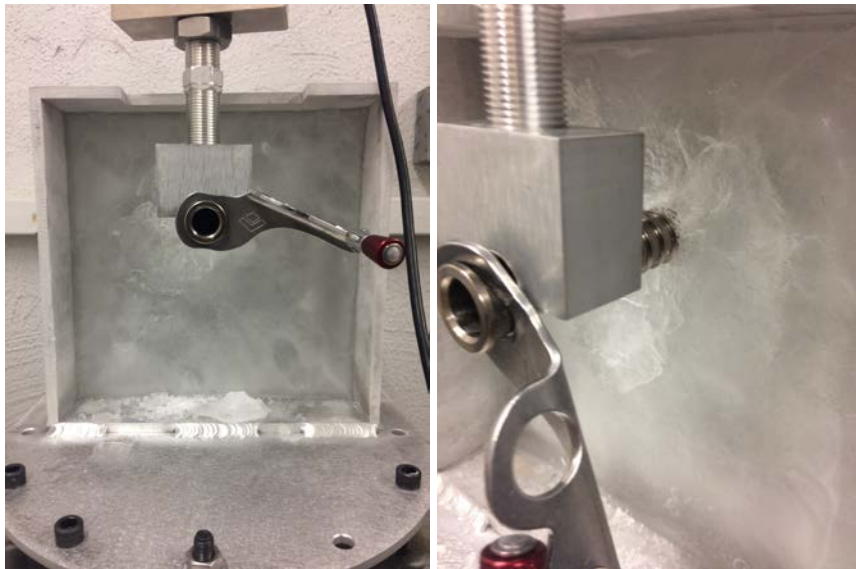


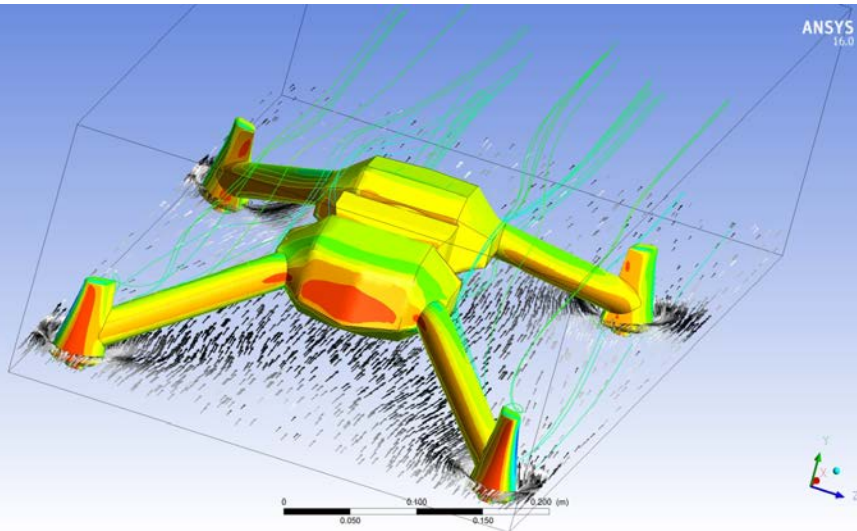
- Mission Concept
- Characterization of Enceladus Vent Environment
- Trade Studies
- Planetary Protection
- **Experimental Studies**
- Mechanical Prototype Design

- Ice screw is intended for manual operation; no info on needed energy on the catalog specs
- Experiment:
 - Used -20°C chamber at JPL
 - Black Diamon's ice screw; 100 mm in length, 19.5 mm in diameter
 - Insertion depth: 72mm
- Result: ~ 500 J for insertion AND removal
- Extrapolation for ice screws with different sizes
 - Assumption: energy scales with (screw diameter) \times (insertion depth)

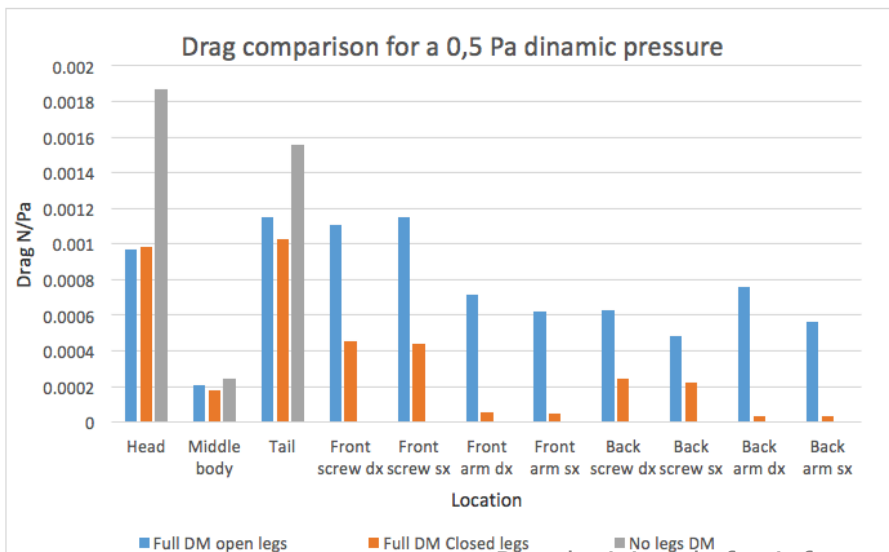


- Experiment setup
 - Used a pressing stand with max load of 40 klbs at JPL
 - Black Diamon's ice screw; 100 mm in length, 19.5 mm in diameter
 - Manufactured ice container with screw attachment made of Al 7075 T3
 - Made ice in a cold chamber at -10°C .
 - Insert a screw horizontally; press the screw downwards until ice breaks
 - Measure the max load
- Results were used to estimate the necessary screw insertion depth for a given drag force exerted on DM





| Aerodynamic drag (N) for 10^5 Pa dynamic pressure | Open limbs | Closed limbs | No limbs |
|---|------------|--------------|----------|
| Total Body + Legs | 1671 | 744 | |
| Total Body | 466 | 437 | 734 |



- Purpose: estimate the drag coefficient (C_D)
- Used the prototype design (detailed in next section) with three configurations:
 - Open limbs
 - Closed limbs
 - No limbs
- Imposed a fixed dynamic pressure of 0.5 Pa
 - k- ϵ model with an inlet speed of 1 m/s and a turbulence of 5%
- Result (closed limb): $C_D A \sim 7.5 \times 10^{-3} \text{ m}^2$, $C_D \sim 1.5$
 - Design optimization could reduce C_D significantly
 - Typical automobile: $C_D = 0.2 - 0.3$
- Estimated drag force by:
 - $F_D = \frac{1}{2} C_D \rho A u^2 = C_D A p$
 - p: dynamic pressure
 - This is a ball park as flow behaves differently in supersonic regime
- Max tolerable dynamic pressure: 5.4×10^5 Pa
 - Assumed 1000N limit for each limb
 - **$\sim 10^5$ Pa would be the safe operational limit**

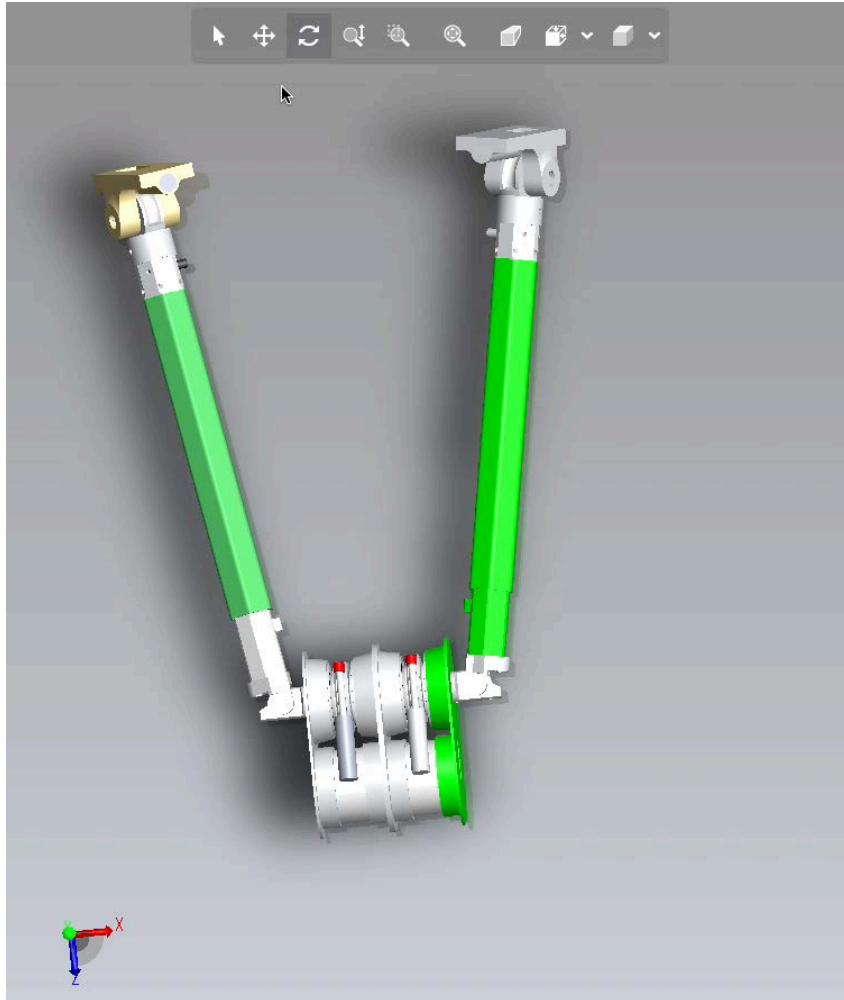


Talk Outline

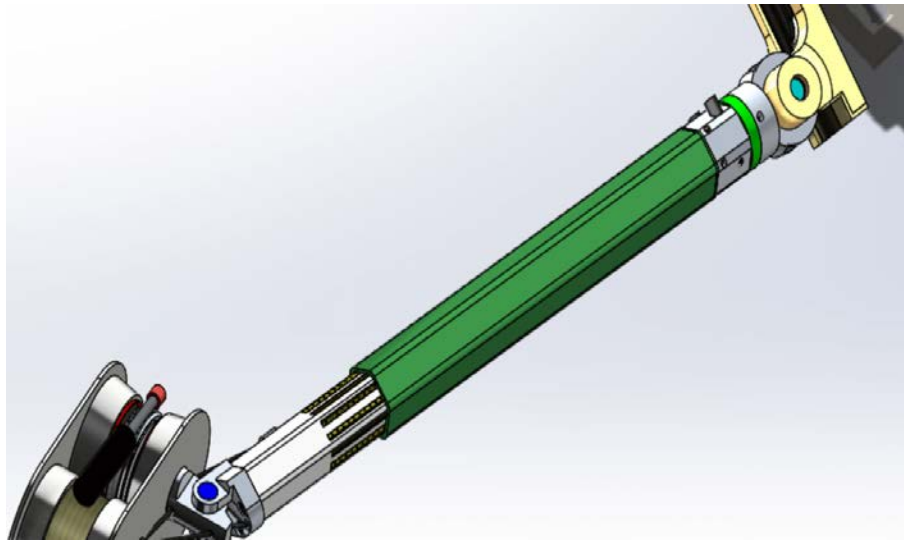


- Mission Concept
- Characterization of Enceladus Vent Environment
- Trade Studies
- Planetary Protection
- Experimental Studies
- **Mechanical Prototype Design**

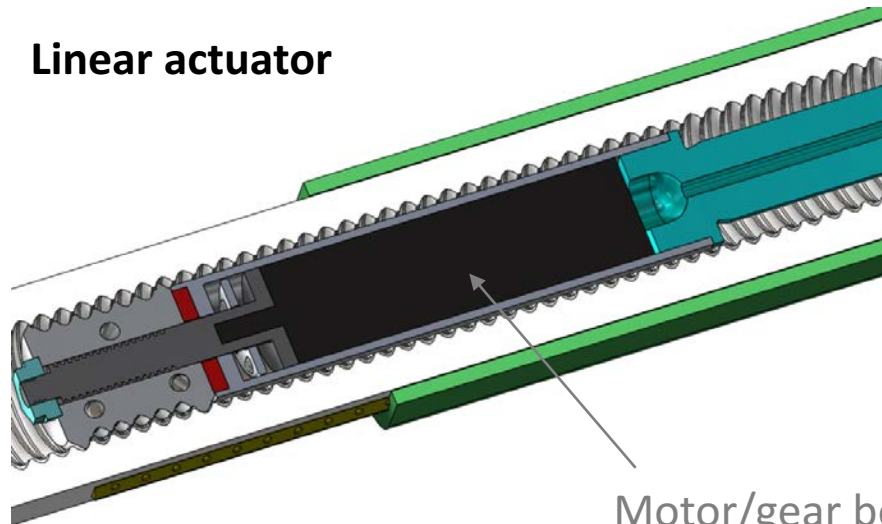
Head/tail section assembly



- A point design, not the optimal one, to serve as a reference point for system trade study
 - Gives conservative estimation of drag force (through CFD), size, mass
 - In particular aerodynamic design could be significantly improved
- Only used existing technologies and commercially available mechanical parts (e.g., motors, gear boxes)
- 5DOF per limb
 - 1 DOF linear joint
 - 2 DOF at shoulder
 - 2 DOF at wrist



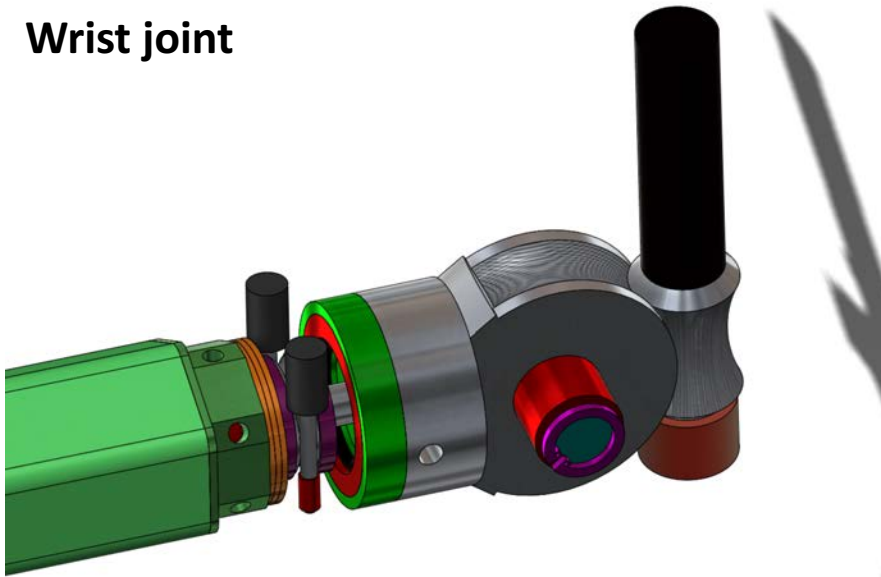
Linear actuator



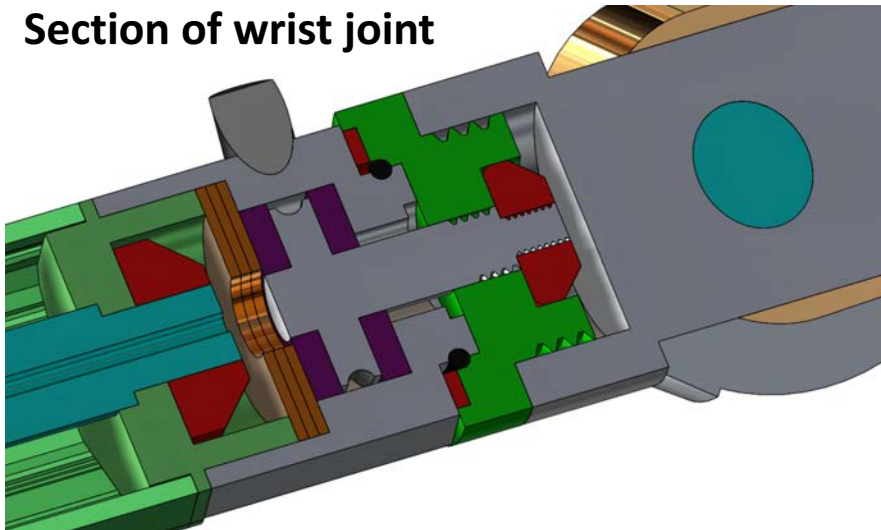
Motor/gear box

- Features a linear actuator
 - Only the linear actuator need to work against the flow
 - Can keep “closed limb” formation to minimize aerodynamic drag
- Uses conventional electro-mechanical actuators
- Designed to support 1000 N of force per limb
- Ball bearing with recirculating balls

Wrist joint

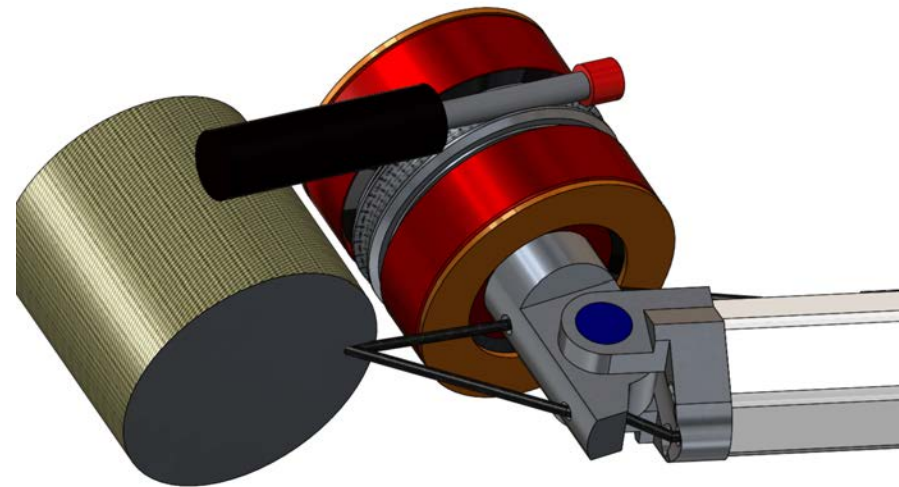


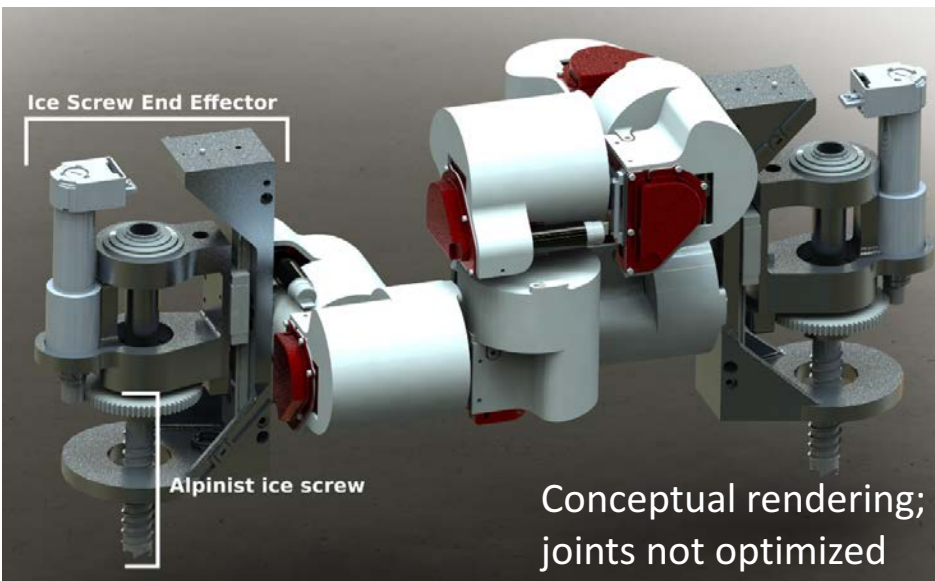
Section of wrist joint



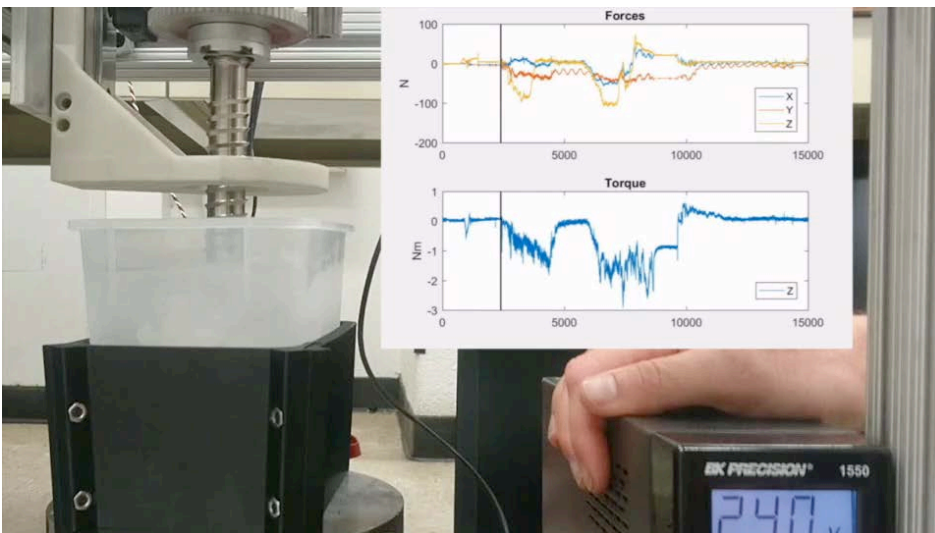
- Wrist joints are actuated by worm gears and motors
- Shoulder joints are actuated by worm gears and tendon actuator
- Shoulder actuators are housed in the head/tail section body

Shoulder joint actuators





- Designed for LEMUR
 - ~10x10x10 cm in size
 - Need to be miniaturized for EVE
- Prototype tested in ice chamber to measure required normal force/torque
- Field test in Helo Cave on Erebus volcano in Antarctica



- Resolve between boiling and cryovolcanic models
 - Probably require observations by ELF
 - Refinement of dynamic pressure/vent size estimates is possible with additional studies of *Cassini* data
- Optimization of DM design
 - Improvement of drag coefficient – $C_D=1.5$ is too high
 - Improve strength of linear actuator
 - Explore alternative DM designs (e.g., snakebot)
- Development of required autonomy capabilities
 - Resilience/goal-directed mobility/graceful degradation/etc
- System trade study of SM, carrier-relay orbiter, and SM-DM interface
- Explore Advanced ideas
 - Interchangeable instrument section
- Consider Europa/terrestrial applications



Selected Reference



- Arakawa, M. & Maeno, N., 1997. Mechanical strength of polycrystalline ice under uniaxial. *Cold Regions Science and Technology*, Volume 26.
- Beverly, J. M., 2009. *Ice Climbing Anchor Strength: An In-Depth Analysis*, s.l.: s.n.
- Boston, P., 2016. *Biovermiculation biopatterns as universal signatures of extant and extinct life*. s.l.:s.n.
- Boston, P. J., Spilde, M. N. & Melim, L. A., 2001. *Cave microbe-mineral suites: best model for extraterrestrial biosignatures!*. s.l., s.n.
- Fuguredo, P. et al., 2003. Locating Potential Biosignatures on Europa from Surface Geology Observations. *Astrobiology*, 3(4).
- Goguen, J. D. et al., 2013. The temperature and width of an active fissure on Enceladus measured with Cassini VIMS during the 14 April 2012 South Pole flyover. *Icarus*, 226(1), pp. 1128-1137.
- Hand, K. P. et al., 2017. *Europa Lander Study 2016 Report: Europa Lander Mission*, s.l.: s.n.
- Hansen, C. J. et al., 2011. The composition and structure of the Enceladus plume. *Geophysical Research Letters*.
- Kehl, F. et al., 2016. In-situ liquid extraction and analysis platform for Mars and ocean worlds. *3rd International Workshop on Instrumentation for Planetary Missions*.
- Kite, E. S. & Rubin, A. M., 2016. Sustained eruptions on Enceladus explained by turbulent dissipation in tiger stripes. *Geophysical Research Letters*.
- Matson, D. L., Castillo-Rogez, J. C., Davies, A. G. & Johnson, T. V., 2012. Enceladus: A hypothesis for bringing both heat and chemicals to the surface. *Icarus*, 221(1), pp. 53-62.
- McKay, C. P., 2004. What is life and how do we search for it in other worlds?. *PLOS Biology*.
- Mitchell, K., 2005. Coupled conduit flow and shape in explosive volcanic eruptions. *Journal of Volcanology and Geothermal Research*, Volume 136, pp. 223-240.
- Porco, C. C. et al., 2006. Cassini Observes the Active South Pole of Enceladus. *Science*, 311(5766), pp. 1393-1401.
- Porco, C., DiNino, D. & Nimmo, F., 2014. HOW THE GEYSERS, TIDAL STRESSES, AND THERMAL EMISSION ACROSS THE SOUTH POLAR TERRAIN OF ENCELADUS ARE RELATED. *Astronomical Journal*, 148(3).
- Sakurai, T. et al., 2015. Studies of melting ice using CO2 laser for ice drilling. *elsevier*, 8 October.
- Spitale, J. N. et al., 2015. Curtain eruptions from Enceladus' south-polar terrain. *Nature*, Volume 521, pp. 57-60.
- Waite, J. H. et al., 2011. *Enceladus' Plume Composition*. s.l., s.n.
- Wilcox, B. H., Carlton, J. A., Jenkins, J. M. & Porter, F. A., 2017. *A Deep Subsurface Ice Probe for Europa*. Big Sky, IEEE, p. 2622.
- Wilhelms, F., Kriews, M. & Dick, D., n.d. *The physical properties of ice with respect to laser light for environmental and industrial applications*. s.l.:s.n.
- Willis, P. A., Mora, M. F. & Creamer, J. S., 2015. Implementation of microchip electrophoresis instrumentation for future spaceflightmissions. *Analytical and Bioanalytical Chemistry*.
- Zimmerman, W., Bonitz, R. & Feldman, J., 2001. *Cryobot: An Ice Penetrating Robotic Vehicle for Mars and Europa*. s.l., s.n.



Questions?

